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WILSON CYCLE STUDIES

NASA GRANT NAG5-585

Semi-Annual Report

January 14, 1988 to July 15, 1988

Effort was concentrated in problems of Continental Evolution and a presentation was made to a workshop on the Deep Continental Growth of South India (Attachment 1).

An interpretation of the lithospheric structure of Africa as related to continental collision (together with its volcanism and topography) has been prepared (with L. D. Ashwal) and a paper on this topic is about to be submitted (see Attachment 2).

No expenditures were charged to the grant during this 6 month period.

Kevin Burke

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Attachment 1 (Semi Annual rept Jan-July) 1988

WORKSHOP ON
THE DEEP CONTINENTAL CRUST OF SOUTH INDIA

Edited by

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Convened by

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HOW WIDELY IS THE ANDEAN TYPE OF CONTINENTAL MARGIN REPRESENTED IN THE ARCHEAN? Kevin Burke, Lunar and Planetary Institute, 3303 Nasa Road One, Houston, TX 77058 and Department of Geosciences, University of Houston, University Park, Houston, TX 77004

Continents are elevated above the ocean floor because continental crusts are made up of material lighter than the overwhelmingly basaltic oceanic crust. The great bulk of igneous rocks less dense than basalt forming today is made at convergent plate boundaries and for this reason processes at convergent boundaries are considered most likely to have been dominant in the production of the continental crust.

Convergent plate boundaries can be characterized as: Island arcs, Andean Margins and Collision zones (both arc-continent collision zones and continent-continent collision zones). Only island-arc convergent boundaries can originate entirely within the ocean (perhaps nucleating on oceanic fracture zones) and for this reason this type of boundary is likely to have been involved in forming the world's first "continental crust" at more than 4 Ga. Compositions of rocks formed at island arc boundaries in the Late Phanerozoic (for example, the Greater Antillean Island Arc [1] show close resemblances to some Archean rocks and it seems likely that this kind of material is widely represented within the Archean although some differences in source magmas and in proportions of rock types have been suggested.

Andean and collisional convergent boundaries are likely to involve (1) contamination of material newly-derived from the mantle by material already in the continental crust and (2) partial melting of that crust. These processes produce recognizable geochemical signatures (e.g. high initial strontium isotopic ratios) which are widespread among Archean rocks.

It therefore seems possible that Andean margins and both kinds of collisional boundaries are represented within the Archean and I here draw attention to a simple structural criterion that may be applied to discriminate between Andean margins and continental collision zones. Continental collision zones are enormous in area (10^6 km^2) (e.g. Tibet today) and have been so in the past, (e.g. the Grenville Province and the Pan African). It is hard to recognize such huge areas among Archean rocks because of the limited extent of most preserved Archean provinces, but the 0.5×10^6 km^2 area of granulite within the Superior Province of Labrador is the most likely candidate. By contrast, Andean margins are long ($\sim 10^3$km) and narrow (as the Andes today) and volcanism within Andean provinces is usually restricted to a narrow zone less than 100 km wide expanding to a broader area (such as in South America today) only in areas of extreme shortening of the basement [2].

The Phanerozoic history of the Andes shows that apart from rafting in of arc and microcontinental material ("terranes" of some authors) which was important in the Paleozoic in the South [3] and has been important again within the last 100 Ma in the North [1], there have been episodes of crestal rifting [4] and marginal basin formation [5] within the Andean arc. Possible analogues of these features are common in the Archean record (e.g. 6).

In summary: Andean margins are likely to be recognized in the Archean as: (1) the site of abundant granodioritic to granitic intrusions with either or both of mantle and older continental isotopic signatures, (2) occupying a length of hundreds of kilometers, but (3) only a width one or two hundred km, (4) cut by mafic dikes representing episodes of extension within the arc, (5) the site of crestal-rift volcanic rocks (like those of Taupo in New Zealand, e.g. [ref. 6] and, (6) the site of marginal basins (like the Rocas Verdes [5]).

ANDEAN ARCHEAN MARGINS?

Burke, K.

Although it is clear that no Archean Andean margins can have survived within continents, Andean margin remains have been recognized in the Superior Province of Canada [ref.7] and the Closepet "granite" of Southern India may represent another example. It seems possible that Andean margins may be rather widely represented among Archean rocks and that there are good possibilities of recognizing them on structural grounds, perhaps complimented by compositional evidence. It seems clear that compositional evidence alone will always be ambiguous because it cannot distinguish Andean from collisional environments [pace, ref. 8].

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Attachment 2 (semi Annual rept Jan-July)
1988

AFRICAN LITHOSPHERIC STRUCTURE, VOLCANISM, AND TOPOGRAPHY

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We interpret the restriction of Cenozoic volcanic rocks of Africa to areas affected by Pan-African reactivation [1-4] and their virtual absence from cratonic areas as evidence that the Pan-African areas are underlain by fertile lithospheric mantle and the cratons by depleted lithospheric mantle. The cratons were formed by assembly of collided island arcs [5], and are underlain by depleted, oceanic-type mantle. Depleted mantle lithosphere was delaminated [6] beneath thickened continental areas during Tibetan-style collision in Pan-African times and replaced by fertile asthenospheric mantle. When the African plate came to rest with respect to mantle circulation patterns at about 30 Ma [7], heating from below extracted magmas from the fertile but not from the depleted lithosphere. As a result, Pan-African reactivated areas display both Neogene elevations and volcanism, whereas cratonic areas display only elevations.

Almost a quarter of a century ago Kennedy [1] and Rocci [2] drew attention to differences between ancient African cratonic areas and those involved in "Pan-African thermo-tectonic events" at about the beginning of Phanerozoic times (500 $\pm$ 200 Ma). This seminal distinction has proved remarkably stimulating both in promoting studies of African tectonics and in studies of continental evolution in general. Kennedy [1] recognized Pan-African areas as characterized by the resetting of isotopic systems in pre-existing continental crust. He chose to call the isotopic resetting a "thermo-tectonic event" because he was uncertain as to how much this kind of areally extensive reactivation resembled the processes that occur in mountain building episodes. Later workers have recognized many more distinctive features of both the cratons and the reactivated areas (which have come to be called products of the "Pan-African Orogeny"). For example, Black and Girod [3] pointed out that Cenozoic volcanic rocks are restricted to reactivated Pan-African and younger orogenic belts around the West African craton and do not occur on that craton. Thorpe and Smith [4] extended this observation to the whole continent showing that although Cenozoic volcanism has been widespread in Africa, there is very little Cenozoic volcanic rock on any of the cratons (Fig. 1).

Dewey and Burke [8,9], in attempting to apply uniformitarian principles to the Pan-African events, emphasized that these terranes resembled, in their vast areal extent, the kind of orogenic process presently resulting from continental collision in the Himalaya and Tibet. They suggested, therefore, that the Pan-African reactivation might have resulted from continental collision. About the same time, Briden and Gass [10], using paleomagnetic data, suggested that the Pan-African represented one of 3 intervals when Africa came to rest with respect to the Earth's magnetic dipole-field and (by inference) the Earth's spin-axis (the other suggested intervals were during the break-up of Gondwana and during the Neogene). They further proposed that these stationary periods might be linked to episodes of magmatic activity. Numerous authors inferred that the Pan-African might have been an "ensialic" orogeny, several comparing it with the Hercynian Orogeny of Europe [e.g. 11]. This non-uniformitarian approach, however, has been generally abandoned. Most early discussions of Pan-African tectonics concentrated on the properties of the continental crust, although a few [e.g. 12] extended consideration to the underlying mantle lithosphere. In recent years much interest has developed in the African mantle lithosphere particularly in cratonic areas where the diamondiferous kimberlites have come to be recognized as powerful probes.

The sub-cratonic lithosphere of Africa is becoming well-characterized. Studies of diamond inclusions, xenocrysts and xenoliths in kimberlites suggest that the cratons have deep lithospheric roots composed mainly of peridotites that have been strongly depleted in basaltic (and possibly even komatiitic) components [13]. Jordan [14] suggested that the root of mantle lithosphere beneath cratonic areas was likely to extend to depths of about 200 km. Isotopic work on garnet inclusions in diamonds has yielded Sm-Nd model ages of 3.2-3.3 Ga, indicating that these lithospheric roots are about as ancient as the crustal rocks of the overlying cratons [15]. De Wit [16], elaborating earlier ideas [16], has described how the cratons (like the greenstone belt terranes of North America [e.g. 17]) can be regarded as having been assembled by repeated and complex collisions of ancient island arcs, a process leading to formation of a deep keel of sub-oceanic depleted lithospheric mantle beneath the cratons. Haggerty [18] has summarized the later history of the cratonic lithosphere involving episodic, locally hydrous metasomatism contributing to limited further lithospheric evolution.

Geophysical studies [e.g. 12] indicate that the mantle lithosphere beneath Pan-African reactivated areas is thinner, generally contributes more to surface heat flow, and is of lower seismic velocity than the mantle beneath the cratons. These properties suggest to us that there are two different kinds of mantle lithosphere beneath Africa, and that the mantle lithosphere under the reactivated areas may be less depleted in basaltic components than that below the cratons.

It has been suggested that a more depleted, thicker mantle lithosphere was generally produced during the Archean because, to quote Hoffman [19, p. 586]: "...secular decline in mean temperature of the asthenosphere implies a greater depth and volume of melting accompanying mantle upwelling in the Archean, and consequently a thicker, more depleted mantle lithosphere [20,21]." At least in Africa, the tectonics involved in generating the Pan-African reactivated crust and the Archean crust differed greatly, so that differences in the underlying lithosphere may be relatable to specific processes rather than attributed to the general idea of secular variation in "mantle upwelling."

The laterally heterogeneous sub-crustal lithosphere of the African continent can be interpreted as representing the integration of plate tectonic processes operative over almost the entire span of geologic history. A possible sequence of events is illustrated in Fig. 2. Studies of Archean cratons combined with inferences from modern tectonic environments are consistent with the hypothesis that ancient continents formed by repeated collisions of island arcs (Fig. 2a) [e.g. 16,22]. Continents assembled in this way are expected to be underlain by lithospheric mantle depleted in crustal components, and this has been borne out by isotopic measurements on igneous rocks that have penetrated the cratons (as well as on their contained xenoliths). For example, igneous rocks represented by mantle-derived melting products of a variety of ages in the Archean Superior Province of the Canadian Shield consistently show depleted signatures in the Rb-Sr, Sm-Nd and Pb-Pb isotopic systems, indicating the integrity of underlying depleted mantle lithosphere there since about 2.7 Ga [23-26].

We consider that during collisions of continental masses in Tibetan-style convergence zones, underlying depleted mantle lithosphere is detached from overlying crust, and is replaced by comparatively "fertile" asthenospheric mantle which has not been subjected to previous depletion in crustal components (Fig. 2d). This process is called lithospheric "delamination" and has been suggested to be an important element in both mantle and crustal evolution [e.g. 27,28]. The geometry we suggest in Figure 2d differs from that originally suggested by Bird [6], but it is close to that envisaged by later workers. Although the density of depleted mantle is likely to be less than that of fertile mantle (because of a lower content of Fe) the difference is small and sinking will occur if, for example, a small amount of garnet-bearing lower crustal mafic rock is delaminated along with the mantle lithosphere.

Figure 2e shows a post-collisional configuration. After thickened crust returns to normal thickness by erosion, rifting and isostatic uplift, those continental areas that have experienced Tibetan-style collision and associated Pan African type crustal magmatism with widespread resetting of isotopic clocks overlie fertile mantle lithosphere, but cratons overlie depleted mantle.

We suggest that Cenozoic volcanic rocks were extracted only from fertile mantle underlying areas of Pan-African reactivation (Fig. 2f). The predominantly alkaline character of these volcanic rocks may be taken as evidence for their derivation from undepleted mantle sources, although we recognize the role played by fractionation and crustal contamination in producing similar effects. Under cratonic crust, the depleted mantle was generally unable to yield magma, and these lithospheric regions responded to heating from below only by lithospheric thinning and elevation increases. Where rare Cenozoic rocks do occur on the cratons, as in the Virunga Province they appear to have risen from very great depths apparently below depleted mantle lithosphere [29].

The stationary behavior of the African continent over the convecting mantle since about 30 Ma ago [7] may have been an important factor in concentrating sub-lithospheric heat sources [10], resulting in mid-plate volcanism where fertile mantle was available. Although a stationary continental mass (such as Africa has been for the past few 10's of Ma) may not be necessary for eruption of continental volcanics on top of reactivated terranes, it probably facilitates the melting process.

The lateral distribution of African lithospheric types may also have controlled relative elevation. Depleted mantle can be expected to be less dense than fertile mantle [30] and cratonal areas underlain predominantly by depleted mantle are expected to stand higher than reactivated terranes. This would account for the restriction of Mesozoic and Cenozoic marine deposits to Pan-African reactivated areas, as noted by Kennedy [1]. In a similar way Phanerozoic flooding of Proterozoic North America has been more frequent than that of Archean North America [e.g. 19, p. 586].

A possible consequence of the process we envisage is that isotopic compositions of continental extrusives and intrusives might be usable, in some cases, as indicators of the prior history of crust that has passed through a later collisional experience. For example, the depleted isotopic signature of pre-collisional mantle-derived magmatic products in continental crust, such as the Mid-Proterozoic anorthosite massifs of the Grenville Province [31] may indicate that the continental crust into which they were intruded had not experienced collisional events before the Grenvillian event at about 1 Ga.

Unfortunately, isotopic compositions other than those indicative of derivation from depleted mantle will in many cases be ambiguous because of the difficulties in distinguishing fertile or enriched mantle signatures from the effects of crutal assimilation. It is intriguing, however, to consider that although the depleted mantle lithosphere that underlay much of the Grenville Province from 2.0 to 1.2 Ga was removed by delamination during collisional orogeny, an indirect record of its character is preserved in the anorthosites emplaced into the continent before collision.

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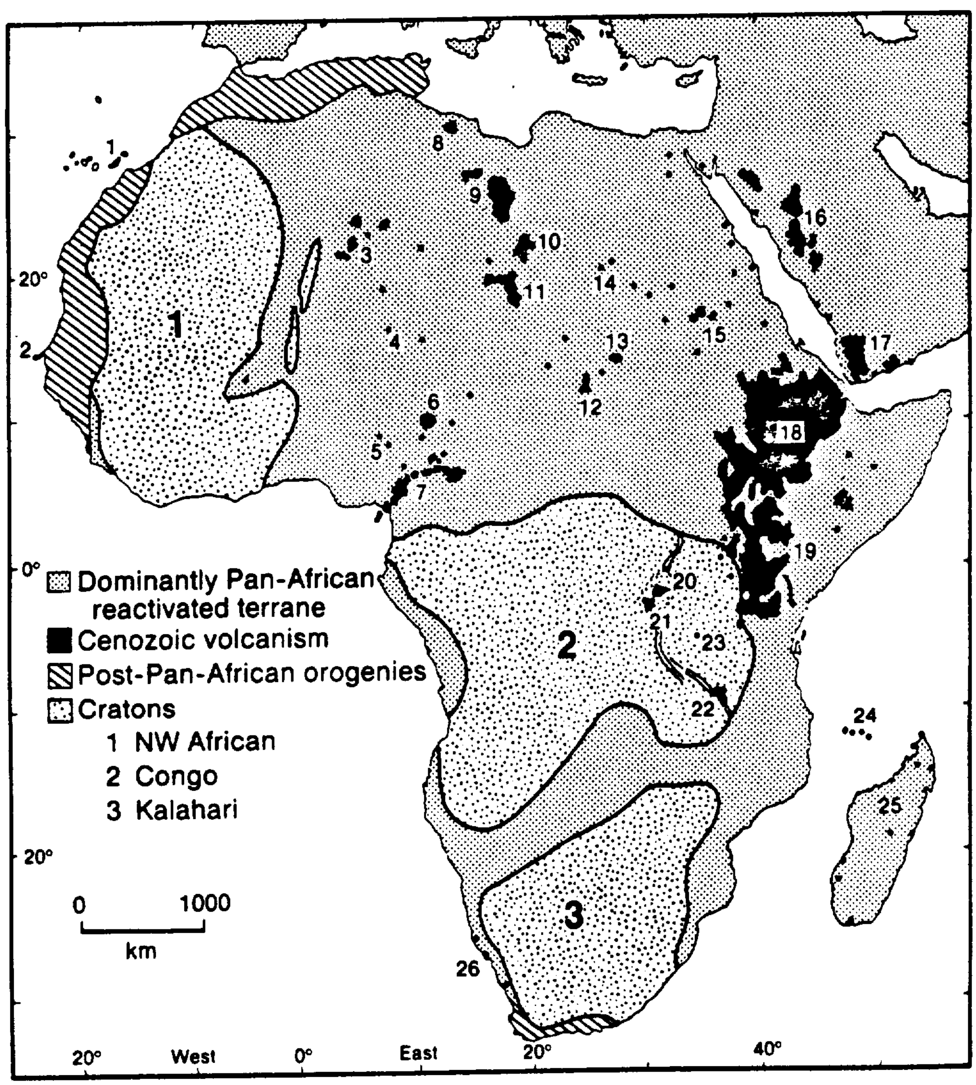
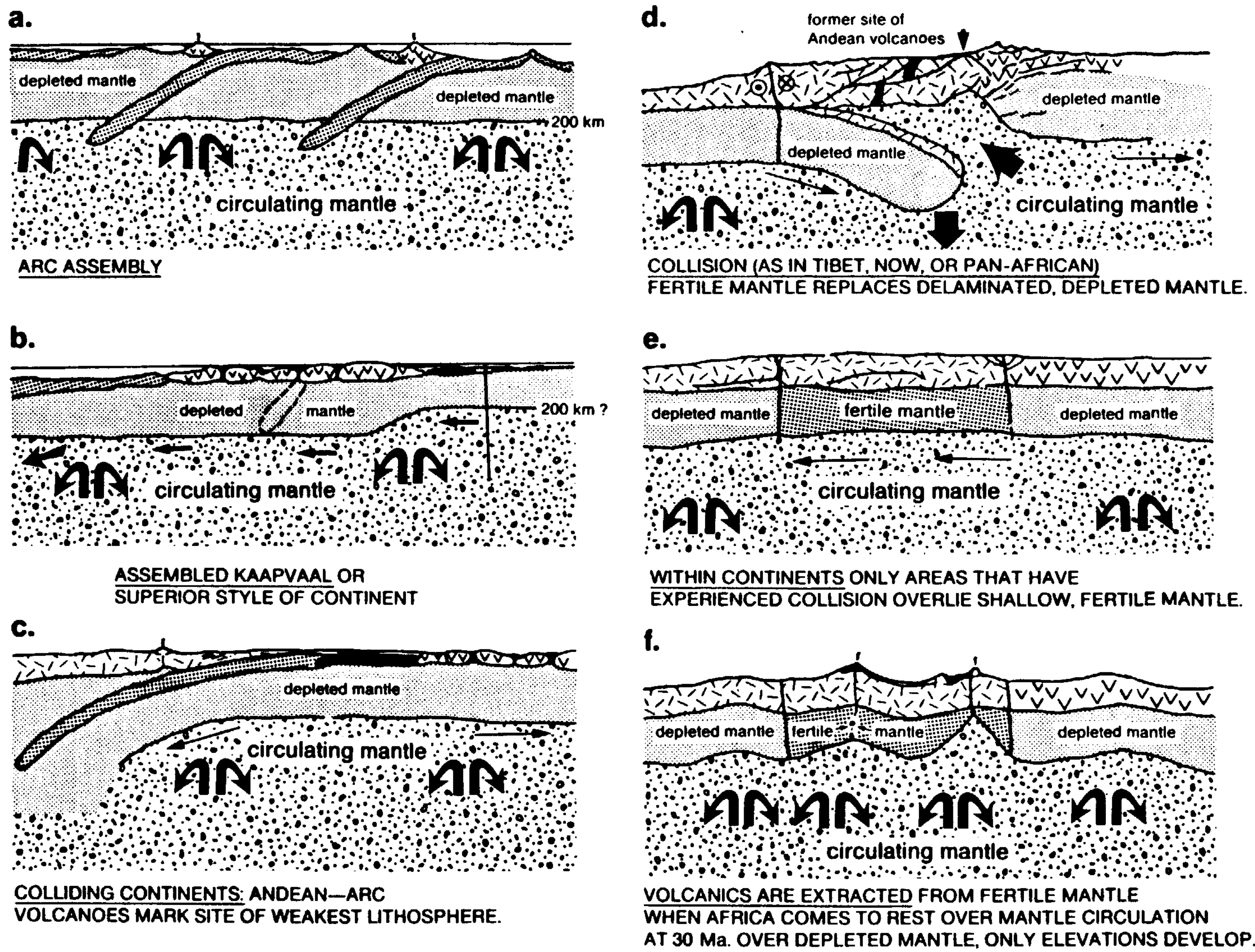
Figure Captions

Fig. 1. Distribution of Cenozoic volcanic rocks in Africa showing that they are almost completely absent from cratonic areas. Individual volcanic areas are: 1 = Canary Islands; 2 = Dakar; 3 = Hoggar; 4 = Air; 5 = Jos; 6 = Biu; 7 = Cameroon Line; 8 = Tripolitania; 9 = J. Haruj; 10 = Eghei; 11 = Tibesti; 12 = J. Marra; 13 = Meidob; 14 = J. Uweinat; 15 = Bayuda; 16 = West Arabia; 17 = South Africa and Aden; 18 = Ethiopia; 19 = East African (Kenyan) Rift; 20-22 = West African Rift with 20 = Virunga; 21 = Kivu; 22 = Rungwe; 23 = Igwisi Hills; 24 = Comores; 25 = Madagascar; 26 = Southwest Africa. Modified from Thorpe and Smith [4].

Fig. 2. Proposed sequence of events in the history of the African lithosphere. Repeated collisions of island arcs (a) results in assembled continent underlain by depleted mantle. Continued plate motions (c) result in Tibetan-style continental collision (d), during which depleted mantle is delaminated and replaced by "fertile" asthenospheric mantle. This results in laterally heterogeneous sub-continental lithosphere (e) in which only those parts of the crust having experienced Tibetan-style reactivation are underlain by fertile mantle. When Africa came to rest with respect to the mantle circulation pattern at about 30 Ma , heating from below produced volcanism only in reactivated areas underlain by fertile mantle lithosphere. Other areas responded to heating only by elevation increases.



Ashwal & Burke Fig. 2



Ashwal & Burke Figure 2.